Evaluation of Alternative Rebuilding Strategies for Pribilof Islands Blue King Crabs

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Jie Zheng and Douglas Pengilly

REGIONAL INFORMATION REPORT[1] NO. 5J03-10

Alaska Department of Fish and Game
Division of Commercial Fisheries
P.O. Box 25526
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[1]The Regional Information Report Series was established in 1987 to provide an information access system for all unpublished divisional reports. These reports frequently serve diverse ad hoc informational purposes or archive basic uninterpreted data. To accommodate timely reporting of recently collected information, reports in this series undergo only limited internal review and may contain preliminary data, this information may be subsequently finalized and published in the formal literature. Consequently, these reports should not be cited without prior approval of the author or the Division of Commercial Fisheries.

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EXECUTIVE SUMMARY

The Pribilof Islands blue king crab (*Paralithodes platypus*) stock was declared "overfished" by the National Marine Fisheries Service due to low stock abundance in 2002. Under the Magnuson-Stevens Act a rebuilding plan for this stock must be adopted by the North Pacific Fishery Management Council (NPFMC) within a year of the overfished declaration. Integral to a rebuilding plan for this stock is a harvest strategy that allows for the stock to rebuild to the rebuilt level as defined in the FMP within the time-frame criteria established by the Magnuson-Stevens Act. The NPFMC is scheduled to adopt a rebuilding plan for this stock at their meeting during the week of October 6, 2003. The Alaska Board of Fisheries is expected to promulgate regulations establishing the harvest strategy (i.e., the GHL-setting rule) portion of that rebuilding plan on October 4, 2003, immediately prior to the NPFMC meeting. This report provides an evaluation of alternative harvest strategies for the Pribilof Islands blue king crab fishery relative to their effectiveness in allowing for stock rebuilding.

Three broad alternatives for a harvest strategy were examined: status quo management, a harvest strategy that allows for some directed fishing before the stock rebuilds to the target biomass, and a harvest strategy that allows for no directed fishing before the stock rebuilds to the target biomass. At least two options were examined for each alternative, resulting in a total of eight options that were analyzed. As part of this effort, we updated an existing four-stage, catch-survey stock assessment model for male crabs, developed a similar model for female crabs, and constructed a stock-recruitment model to evaluate alternative rebuilding strategies.

The association between recruitment and spawning biomass for Pribilof Islands blue king crabs was very weak, and spawning biomass explained very little recruitment variation. The stock–recruitment (S–R) analyses indicate existence of a quasi-cyclic annual recruitment pattern, with periods of strong and weak recruitment alternating every few years, which caused cyclic spawning biomass over time. The four-stage model and stock–recruitment relationships were combined in a computer simulation model to estimate rebuilding time periods and rebuilding probabilities for Pribilof Islands blue king crabs under each of the eight harvest strategy options. With the base model (i.e., the model assuming a cyclic S–R relationship and a 20% handling mortality rate) the rebuilding time periods at 50% probability are 9 years without a fishery before rebuilding and 9 and 10 years with the other options. The rebuilding time periods at 90% probability range from 11 to 25 years. Rebuilding time periods and probabilities depend on assumptions on future recruitment and handling mortality rate. The status quo strategy as presented to the Alaska Board of Fisheries in 1990 has a relatively high mean yield, but also has a high probability of being below the minimum stock size threshold (MSST) and requires a long time to rebuild the stock. Four options provide relatively high mean yields, short timeframes for rebuilding, and low proportions of years with the stock below MSST. They are strong candidates for a rebuilding harvest strategy. Each provides for some directed harvest prior to the stock being rebuilt, which may alleviate some of the financial burden on the affected communities.

ISSUES AND PURPOSE

The king and Tanner crab stocks of the Bering Sea/Aleutian Islands (BS/AI), including the Pribilof Islands blue king crab (*Paralithodes platypus*) stock, are managed by the State of Alaska under the federal Fishery Management Plan for Bering Sea/Aleutian Islands King and Tanner Crabs (FMP; NPFMC 1998). The FMP establishes a State-Federal cooperative management regime in which the management of BS/AI king and Tanner crabs is deferred to the State of Alaska with Federal oversight. Under the FMP, management measures fall into three categories: (1) those that are fixed in the FMP under Council control, (2) those that are frameworked, which the State can change following criteria outlined in the FMP, and (3) those measures under complete discretion of the State. In particular, guideline harvest levels (GHLs) and the harvest strategies that are used to determine GHLs are Category 2 management measures under the FMP. Among other considerations, GHLs must be determined so that overfishing as defined in the FMP does not occur. Additionally, under the Magnuson-Stevens Fishery Conservation and Management Act (Magnuson-Stevens Act) GHLs must be set to allow for rebuilding of stocks that have been declared "overfished."

The Pribilof Islands blue king crab stock was declared "overfished" by the National Marine Fisheries Service (NMFS) after the estimated spawning biomass (i.e., the estimated total mature male and female biomass) was calculated to be below the minimum stock size threshold (MSST) established for this stock in the FMP; the spawning biomass estimated for 2002 was 4.5 million pounds as compared to the MSST of 6.6 million pounds (NPFMC 2002). Under the Magnuson-Stevens Act a rebuilding plan for this stock must be adopted by the North Pacific Fishery Management Council (NPFMC) within a year of the overfished declaration. Integral to a rebuilding plan for this stock is a harvest strategy that allows for the stock to rebuild to the biomass of maximum sustainable yield (B_{MSY}) as defined in the FMP within the time-frame criteria established by the Magnuson-Stevens Act.

The NPFMC is scheduled to adopt a rebuilding plan for this stock at their meeting during the week of October 6, 2003. The Alaska Board of Fisheries is expected to promulgate regulations establishing the harvest strategy (i.e., the GHL-setting rule) portion of that rebuilding plan on October 4, 2003, immediately prior to the NPFMC meeting.

The purpose of this report is to evaluate alternative harvest strategies for the Pribilof Islands blue king crab fishery relative to their effectiveness in allowing for stock rebuilding. A brief summary of the status quo determination of GHLs for the Pribilof Islands blue king crab fishery is presented. Then, the computer simulation results from alternative harvest strategies, and the options for alternatives, are summarized and compared. Finally, merits for each alternative harvest strategy relative to a rebuilding plan are discussed.

STATUS QUO DETERMINATION OF GHLS

Currently there is no harvest strategy in regulation for the Pribilof Islands blue king crab fishery. However, a harvest strategy for Pribilof Islands blue king crabs was presented to and approved by the Alaska Board of Fisheries (BOF) at their spring 1990 meeting. That harvest strategy first became effective for use during the 1990 season, which had a regulatory opening date of September 1. The harvest strategy is described in Pengilly and Schmidt (1995) and has three components:

1) A threshold of 0.77 million males ≥120-mm carapace length (CL) – if the estimated abundance of males ≥120-mm CL is less than 0.77 million, the fishery remains closed for the season. Note that 120-mm CL is not the minimum legal size; it is the harvest strategy's operational definition for minimum size of functional maturity of males. Minimum legal size is 6.5-inches carapace width (CW), which corresponds to approximately 135-mm CL.
2) A 20% rate of exploitation on males ≥120-mm CL – if the fishery is opened, the target number of legal males for harvesting is equal to 20% of the estimated abundance of males ≥120-mm CL, unless constrained by component (3), below.
3) The harvest guideline is constrained to not exceed 60% of the estimated abundance of legal males (under the current 6.5-in minimum legal size, legal males are generally ≥135-mm CL).

Since 1990, ADF&G has actually managed the Pribilof Islands blue king crab fishery more conservatively than by strict application of the harvest strategy. That practice was seen as warranted due to:

1) The declines in stock levels during the mid-to-late 1980s that resulted in a fishery closure during 1988 and 1989;
2) The low precision for the population abundance estimates afforded by survey data for this stock; and
3) Concerns related to manageability of the fishery with a potentially large fleet.

To partially address those concerns, management of the Pribilof Islands blue king crab fishery has been closely tied to management of the Pribilof Islands red king crab (*Paralithodes camtschaticus*) fishery and the St. Matthew blue king crab fishery. Since 1993 the opening dates of the St. Matthew blue king crab and Pribilof Islands red and blue king crab fisheries have been coincident. The intent of coincident opening dates was to distribute the fleet between the St. Matthew and Pribilof Islands fisheries, thereby decreasing effort in and increasing manageability of both fisheries. Additionally, since the Pribilof Islands blue king crab fishery reopened in 1995, both the Pribilof Islands red king crab and blue king fisheries have been opened and closed together with a pooled red-and-blue king crab GHL. Managers felt that opening the Pribilof Islands king crab fishery under a pooled red-and-blue king crab GHL would buffer the effects of abundance estimation in setting the GHL. The pooled GHL was determined so that the harvest would not exceed 20% of the estimated abundance of males ≥120-mm CL from either stock. Additionally, if abundance of one stock was lower than estimated, fishers would be able to switch effort to the more abundant stock.

Decisions on opening the Pribilof Islands blue king crab fishery and GHLs for opened fisheries during 1990–2002 are summarized in Table 1. The fishery remained closed during 1990–1994, the first five years following adoption of the present harvest strategy, although point estimates for "mature males" (i.e., males ≥120-mm CL) were above the threshold of 0.77 million. The fishery closures in those years were due to the high uncertainty on the abundance estimates of mature males, coupled with the concerns for reopening the stock to fishing after the declines observed in the late 1980s.

Although the lower confidence bounds for annual stock abundance estimates continued to fall below the threshold value, the fishery opened for the 1995 season and reopened for each season through 1998. The point estimate for abundance of mature males for each year during 1995–1998 was above the threshold value and several considerations lessened the conservation concerns on opening the fishery. Despite the poor precision of annual abundance estimates, the series beginning in 1990 of annual point estimates of abundance that were above the threshold value provided some confidence that the stock could be considered above threshold during 1995–1998. Changes in management practices beginning in 1995 that linked the management of red and blue king crab fisheries in the Pribilof Islands provided additional confidence to managers that the fishery could be prosecuted while addressing conservation concerns.

In the 1995 fishery season, managers allowed blue king crabs to be harvested as part of a combined blue and red king crab GHL that was determined by a 10% exploitation rate applied to the estimated abundance of red king crab males ≥120-mm CL (Table 1). Results of the 1995 fishery season, in which blue king crabs accounted for 1.3 million pounds of the total 2.1 million pounds harvested, gave fishery managers greater confidence in the abundance estimates for the blue king crab stock. The 1996 through 1998 fishery seasons were each prosecuted under a combined GHL for red and blue king crabs.

The fishery for blue king crabs in the Pribilof Islands closed in 1999 when the abundance of males ≥ 120-mm CL was estimated at 0.8 million (Zheng and Kruse 1999). Although the 1999 point estimate was slightly above threshold, the 1999 season was closed due to concerns raised by a trend of declining abundance, estimated low abundance of prerecruits, low precision of abundance estimates, and past fishery performance below expectations. Additionally, the closure of the St. Matthew blue king crab fishery in 1999 raised concerns that participation in a Pribilof Islands king crab fishery could increase to an unmanageable level. The point estimate for mature-sized male blue king crabs in the Pribilof Islands has been below the stock threshold for a fishery opening and the fishery has remained closed from 2000 through 2002. Because of uncertainties with red king crab stock abundance estimates and concerns with the potential for bycatch of blue king crabs as the blue king crab stock approached and fell below MSST, the fishery for red king crabs in the Pribilof Islands was also closed for the 1999–2002 seasons.

In summary, since 1990 status quo management of the Pribilof Islands blue king crab fishery has been driven by the need to address concerns of poor precision in stock abundance estimation and concerns of fishery manageability during a period of low stock abundance. Because of high uncertainty in stock abundance estimation, the fishery was not opened until the point estimate for mature-sized (≥120-mm CL) males was above threshold for six consecutive years. The basis for the combined red and blue king crab GHLs varied over the four seasons that the fishery was opened (1995–1998; Table 1). However, the harvest as a percentage of annual stock abundance indices was relatively stable: 4%–5% of the estimated mature biomass, 8%–15% of the estimated abundance of legal males, and 6%–11% of the estimated abundance of mature-sized males (Table 2). In particular, the estimated harvest rate on mature-sized males was roughly one-half or less of the 20% specified in the harvest strategy adopted by ADF&G in 1990 (Pengilly and Schmidt 1995). Since 1990, with the intent of buffering effects on the stock due to errors in GHL specification and of reducing fishery effort to manageable levels, the fishery was opened only when both the Pribilof Islands red king crab and the St. Matthew blue king crab fisheries were opened. Finally, during periods of stock decline to or below MSST, concerns about bycatch of Pribilof Islands blue king crabs have been addressed by closing the Pribilof Islands red king crab fishery.

ALTERNATIVE HARVEST STRATEGIES

Three alternative approaches to harvest strategies, including status quo management, for Pribilof Islands blue king crabs were considered. At least two options for each alternative were examined and analyzed. The three alternatives were:

- Alternative 1: The status quo harvest strategy
- Alternative 2: Allow for some directed harvest before the stock rebuilds to B_{MSY}
- Alternative 3: Allow for no directed harvest before the stock rebuilds to B_{MSY}

The alternatives and options for alternatives differ from each other in the stock threshold criteria for opening the fishery, the harvest rate applied to what are considered mature males for management purposes (i.e., males ≥120-mm CL), and the maximum allowed harvest rates on legal-sized males (6.5-inches CW, corresponding to approximately 135-mm CL). Threshold criteria differ among alternatives and options for alternatives in the stock level defined as threshold and in the number of consecutive years that the stock is above threshold. Some options require that the stock size estimate be above threshold for two consecutive years before a fishery opening; that criterion is intended to provide greater assurance that the stock is indeed above threshold before reopening the fishery. In each alternative, and option for each alternative, a minimum GHL of 0.5 million pounds is used as a measure to promote manageability of the fishery. The minimum GHL had not been specified in management of this stock prior to specification of these alternatives.

Alternative 1: The Status Quo Harvest Strategy

Two options, 1A and 1B, for Alternative 1 (status quo management) were examined. Option 1A is the harvest strategy for Pribilof Islands blue king crabs developed by ADF&G in 1990 and described by Pengilly and Schmidt (1995). Actual management of the Pribilof Islands blue king crab stock since development of the harvest strategy for Pribilof Islands blue king crabs has been more conservative than Option 1A, however (see above). Accordingly, Option 1B was also examined as a harvest strategy that more closely reflects the more conservative "status quo management in practice."

Components of Options 1A and 1B are:

- Option 1A (status quo on paper):
  1) Threshold: 0.77 million males ≥120-mm CL
  2) Opens: in 1st year stock is above threshold
  3) Harvest rate on mature males: 20% of survey estimate
  4) Cap on harvest of legal males: 60% of survey estimate
  5) Minimum GHL: 0.5 million pounds

- Option 1B (status quo in practice):
  1) Threshold: 1.00 million males ≥120-mm CL
  2) Opens: in 2nd consecutive year stock is above threshold
  3) Harvest rate on mature males: 10% of survey estimate
  4) Cap on harvest of legal males: 20% of survey estimate
  5) Minimum GHL: 0.5 million pounds

Alternative 2: Allow for Some Directed Harvest Before the Stock Rebuilds to B_{MSY}

Harvest strategies analyzed under Alternative 2 allow for some directed harvest prior to the time that the stock attains B_{MSY}. In each option harvest rates are lower at lower stock levels to increase the opportunity for rebuilding at low stock levels while allowing for some directed harvest.

Options 2A and 2B allow for directed harvest when the stock is above the MSST overfished level, 6.6-million pounds of spawning biomass (total mature male and female biomass). Option 2B is more conservative than Option 2A, with stricter criteria for a fishery opening, and lower harvest rates when the fishery opens. Options 2C and 2D have a higher stock threshold than MSST: 7.5-million pounds of males ≥120-mm CL and females ≥100-mm CL. Option 2C and 2D differ from each other in the harvest rate applied to mature male abundance, with Option 2D having the lower harvest rate.

Components of Options 2A to 2D are:

- Option 2A
  1) Threshold: MSST (6.6-million pounds spawning biomass)

2) Opens: in 1st year stock is above MSST
3) Harvest rate on mature males: 10% of survey estimate at MSST, increases linearly with survey estimate of spawning biomass (or proxy thereof) to 20% at B_{MSY}
4) Cap on harvest of legal males: 40% of survey estimate
5) Minimum GHL: 0.5 million pounds

- Option 2B
  1) Threshold: MSST
  2) Opens: in 2nd consecutive year stock is above MSST (6.6-million pounds spawning biomass)
  3) Harvest rate on mature males: 5% of survey estimate at MSST, increases linearly with survey estimate of spawning biomass (or proxy thereof) to 10% at B_{MSY}
  4) Cap on harvest of legal males: 20% of survey estimate
  5) Minimum GHL: 0.5 million pounds

- Option 2C
  1) Threshold: 7.5-million pounds of males ≥120-mm CL and females ≥100-mm CL
  2) Opens: in 2nd consecutive year stock is above threshold
  3) Harvest rate on mature males: 10% of model estimate at threshold, increases linearly with the estimates of total mature biomass to 20% at 25 million males ≥120-mm CL and females ≥100-mm CL
  4) Cap on harvest of legal males: 30%
  5) Minimum GHL: 0.5 million pounds

- Option 2D
  1) Threshold: 7.5 million pounds of males ≥120-mm CL and females ≥100-mm CL
  2) Opens: in 2nd consecutive year stock is above threshold
  3) Harvest rate on mature males: 10% of model estimate at threshold, increases linearly with the estimates of total mature biomass to 15% at 25 million males ≥120-mm CL and females ≥100-mm CL
  4) Cap on harvest of legal males: 30%
  5) Minimum GHL: 0.5 million pounds

Alternative 3: Allow for No Directed Harvest Before the Stock Rebuilds to B_{MSY}

Alternative 3 allows for no fishery on the Pribilof Islands blue king crab stock until the stock level returns to the B_{MSY} level, defined as 13.2 million pounds of spawning biomass in the FMP. Two options are examined. Option 3B is the more conservative of the two options, with a stricter criterion for a fishery reopening and a lower harvest rate when the fishery reopens.

Components of Options 3A to 3B are:

- Option 3A
  1) Threshold: B_{MSY} (13.2-million pounds of spawning biomass)

2) Opens: in 1st year stock is above B_{MSY}
3) Harvest rate on mature males: 20% of survey estimate
4) Cap on harvest of legal males: 40% of survey estimate
5) Minimum GHL: 0.5 million pounds

- Option 3B
  1) Threshold: B_{MSY} (13.2-million pounds of spawning biomass)
  2) Opens: in 2nd consecutive year stock is above B_{MSY}
  3) Harvest rate on mature males: 10% of survey estimate
  4) Cap on harvest of legal males: 20% of survey estimate
  5) Minimum GHL: 0.5 million pounds

EVALUATION OF ALTERNATIVE HARVEST STRATEGIES

Stock Assessment

A four-stage model has been used to assess Pribilof Islands male blue king crabs since 2000 (Vining and Zheng 2003). A female model was developed during this study. For male crabs, the model consists of pre-recruit-2 males (males two molts from becoming legal size, 105–119 mm CL), pre-recruit-1 males (120–134 mm CL), recruits (new-shell, 135–148 mm CL), and post-recruit males (>148 mm CL and old-shell, 135–148 mm CL). For female crabs, the model consists of group 1 (100–109 mm CL), group 2 (110–119 mm CL), group 3 (120–129 mm CL), and group 4 (>129 mm CL). Survey measurement errors were assumed to be log-normally distributed, and a nonlinear least-squares approach that minimizes the measurement errors was used to estimate parameters. The following model parameters were estimated separately for male and female crabs: recruits to the model each year, total abundance in the first year, natural mortality, trawl survey catchabilities for pre-rercuits 1 and 2 (male model) and group 1 (female model), and molting probabilities for pre-rercuits 1 and 2 (male model) and groups 1-3 (female model).

Model estimates of abundance fitted well with NMFS survey area-swept estimates of abundance, especially after 1981 (Figure 1). Area-swept estimates of abundance before 1982 are highly unreliable. Abundance of mature crabs continues to decline from its recent high levels in the mid-1990s. Estimated abundance of both mature males and females in 2002 is close to the historically lowest level observed in 1988.

Stock–Recruitment Relationships

In this study, we used the results from the newly developed catch-survey analysis to model stock–recruitment (S–R) relationships for Pribilof Islands blue king crabs. Recruitment was assumed to occur within 105–119-mm CL to the male model and within 100–109-mm CL to the female model. A time lag of 8 years was assumed from mating to recruitment.

Spawning biomass was estimated as the sum of total biomass of mature females (≥100-mm CL) and mature males (≥120-mm CL).

The association between recruitment and spawning biomass for Pribilof Islands blue king crabs was very weak, and spawning biomass explained very little recruitment variation (Figure 2). The S–R analyses indicate the existence of a quasi-cyclic annual recruitment pattern (Figure 2), with periods of strong and weak recruitment alternating every few years, which caused cyclic spawning biomass over time.

Because of very weak density-dependent effects on recruitment, we modeled the recruitment dynamics with two approaches: (1) random sampling from recruitment estimates from 1978 to 2002 and (2) periodically semi-cyclic with three components (Figure 2): (i) an S–R curve with a flat line for spawning biomass ≥5 million pounds and linearly decreasing to zero when spawning biomass is between 5 and 0 million pounds, (ii) random alternation of high and low recruitment patterns (4–9 years of high and 4–9 years of low) estimated from the recruitment residuals, and (iii) log-normal noises. For a given year, the recruitment was equal to the product of these three components.

Computer Simulations

The four-stage model and S–R relationships were combined in a computer simulation model to estimate rebuilding time periods and rebuilding probabilities for Pribilof Islands blue king crabs under the alternative harvest strategies and, for comparative purposes, under a total closure of the directed fishery (i.e., F=0). Similar to the "rebuilt" definition for eastern Bering Sea Tanner crabs (*Chionoecetes bairdi*) and St. Matthew Island blue king crabs, we define the stock to be "rebuilt" when mature biomass achieves B_{MSY} in two consecutive years. This definition for rebuilt reduces chances of "rebuilding" caused by survey measurement errors or a single strong year class. Model parameters for simulations are estimated in the assessment model and summarized in Table 3.

The primary features of the simulation scenarios are as follows:

- The model was initialized with data on population status for 2002.

- Because of poor data for small crabs, only males ≥105-mm CL and females ≥100-mm CL were modeled. The mature crabs are defined as males ≥120-mm CL and females ≥100-mm CL. The current B_{MSY} (13.2 million pounds, NPFMC 1998) is defined for all male and female blue king crabs based on survey catchability and maturity. Based on the model results from 1983 to 1997, the equivalent B_{MSY} was approximated for mature males ≥120-mm CL and mature females ≥100-mm CL as 10.88 million pounds, and the equivalent MSST was approximated as 5.44 million pounds.

- For each scenario, we simulated the population and fishery for 35 years with 1,000 replicates. The average population status, rebuilding probability (the proportion of replicates at rebuilt status), loss of fishing opportunity (the proportion of replicates with fishery closure), and mean yield from the simulations were summarized to compare the alternatives and options for alternatives.

- Recruitment was modeled with two approaches: (1) random sampling from recruitment estimates from 1978 to 2002 and (2) a cyclic S–R relationship. We used approach (2) as the base model and approach (1) for sensitivity studies.

- Handling mortality rate of captured, but discarded sublegal males was assumed to be 20% for the directed crab fishery. Sensitivity to assumed handling mortality rate was examined by assuming alternative 0% and 50% handling mortality rates.

- Because few Pribilof Islands blue king crabs were caught as bycatch from groundfish fisheries, no bycatch mortality from groundfish fisheries was included in the simulations.

- An assessment error with a standard deviation of 0.3 was assumed. Assessment errors were applied to the abundance in the initial year and the abundance used to compute GHLs.

Results and Discussion

Simulated results are illustrated in Figure 3 and summarized in Table 4. With the base model (i.e., the model assuming a cyclic S–R relationship and a 20% handling mortality rate), the rebuilding time periods at 50% probability are 9 years without a fishery before rebuilding (T_{min}) and 9 and 10 years with the other options. The rebuilding time periods at 90% probability range from 11 to 25 years. Because T_{min} is less than 10 years, the maximum rebuilding time period, T_{max}, should be 10 years (Restrepo et al. 1998). Due to the low population abundance, the fishery might be closed about 50% or more of the time within a 35-year horizon. Options 1A and 2A have the highest mean yield among all eight options, but also have the highest probabilities of spawning biomass falling below MSST and require the longest times to rebuild the stock. By comparison, Options 1B, 2B, 2C, and 2D have shorter rebuilding times while producing relatively high mean yields. Hence, under the base model scenario, Options 1B, 2B, 2C, and 2D are strong candidates for a rebuilding harvest strategy. Option 3B also has a short rebuilding time and low probability of spawning biomass falling below MSST, but also shows some reduction in yield relative to Options 1B, 2B, 2C, and 2D.

Rebuilding time periods and probabilities also depend on assumptions about future recruitment and handling mortality rate (Table 4). At 10% rebuilding probability, rebuilding time periods are longer for all options under a cyclic S–R relationship than under random recruitment because the stock has been in a period of declining recruitment (Figure 2) and the cyclic recruitment continues that trend. For high rebuilding probabilities (90%), rebuilding time periods are much shorter under a cyclic S–R model than under random recruitment because the cycle deterministically turns to high recruitment after a certain number of years. Probabilities of spawning biomass falling below MSST are much lower under random recruitment than under a cyclic S–R model.

Using the base model, rebuilding times and proportions of the next 10 years with the stock below MSST under Options 1B, 2B, 2C, 2D, and 3B are comparable to those under a total fishery closure (F=0.0). However, in the long term (20 years or more), the proportion of years with the stock below MSST can be expected to be higher under any of the examined harvest strategies than when the directed fishery is completely closed. Under the base model, long-term proportions of years below MSST for Options 1B, 2B, 2C, 2D, and 3B are close to that of a total fishery closure when the handling mortality is assumed to be 0.2 or less. Under the random recruitment model, however, Options 1B and 3B have rebuilding times and proportion of years below MSST most comparable to those of a total fishery closure.

Handling mortality rate for blue king crab bycatch from the directed fishery is not well known. In our study of the red king crab (*Paralithodes camtschaticus*) fishery in Bristol Bay, increased handling mortality in our model resulted in lower optimal harvest rates and higher optimal threshold levels (Zheng et al. 1997). For the Bristol Bay Tanner crab fishery, we found that handling mortality had similar, but less pronounced, effects because of low catchability for females (Zheng and Kruse 1999). Based on limited observer data, catchability of sublegal male and female crabs from the directed blue king crab fishery off the Pribilof Islands is similar to or slightly higher than that of Bristol Bay red king crabs. In this study, we considered two extreme handling mortality rates of 0% and 50% in our sensitivity analysis. Overall, higher handling mortality rates increase rebuilding time periods and decrease mean yield. However, it appears that a handling mortality rate within our examined range does not greatly impact rebuilding time periods under the four options we identified as strong candidates for a rebuilding harvest strategy.

Overall, under our base model, T_{min} is 9 years and T_{max} is 10 years. The target rebuilding time period (T_{target}) for each option examined is either 9 or 10 years under our base model, within the T_{min} and T_{max} bounds as required by the Magnuson-Stevens Fishery Conservation and Management Act.

The current Pribilof Islands blue king crab population status is very depressed relative to historical high abundance in the late 1970s (Vining and Zheng 2003), and the stock is very unlikely to rebuild to such high abundance quickly under the current low productivity environment. The rebuilding time may be long even without directed harvest before rebuilding. The key to stock rebuilding is strong recruitment. Currently, however, we don’t understand what caused the poor recruitment during recent years. With a weak S–R relationship, essentially no fishing mortality for several years, and the habitat protection afforded by the 1994 establishment of the Pribilof Islands Habitat Conservation Area (NPFMC 1994), it is difficult to identify additional measures to increase chances of future strong recruitment. Future research may increase our understanding of the recruitment dynamics. Meanwhile, under the current low productivity environment, a conservative harvest strategy is appropriate to assure protection of the stock. Our analysis indicated that harvest strategy Options 1B, 2B, 2C, and 2D provide such protection to the stock while allowing the opportunity for directed fishing prior to the stock achieving the target level for rebuilding.

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Table 1. Fishery guideline harvest level (GHL) decisions for the Pribilof Islands blue king crab fishery, 1990–2002.

Season	GHL	Basis for GHL
1990	Closed	Extremely poor precision in stock abundance estimates; point estimate above threshold in state harvest strategy, but confidence bound reported as 213% of point estimate
1991	Closed	Poor precision in stock abundance estimates; point estimate above threshold in state harvest strategy, but lower confidence bound below threshold
1992	Closed	Poor precision in stock abundance estimates; point estimate above threshold in state harvest strategy, but lower confidence bound below threshold
1993	Closed	Poor precision in stock abundance estimates; point estimate above threshold in state harvest strategy, but lower confidence bound below threshold
1994	Closed	Extremely poor precision in stock abundance estimates; point estimate above threshold in state harvest strategy, but confidence bound reported as 146% of point estimate
1995	2.5 million pounds, red and blue king crabs combined	10% exploitation rate on estimated abundance of "mature-sized" (≥120-mm CL) red king crab males only
1996	1.8 million pounds, red and blue king crabs combined	20% exploitation rate on estimated abundance of "mature-sized" (≥120-mm CL) blue king crab males only; CSA estimate of legal abundance
1997	1.5 million pounds, red and blue king crabs combined	20% exploitation rate on estimated abundance of "mature-sized" (≥120-mm CL) blue king crab males only; plus 0.2 million pounds for incidental red king crab catch; CSA estimates of blue king crab mature and legal abundance
1998	1.25 million pounds, red and blue king crabs combined	10% exploitation rate on estimated abundance of "mature-sized" (≥120-mm CL) blue and red king crab males; low precision of abundance estimates, poor performance in 1997 fishery
1999	Closed	Declining stock and recruitment trend; poor precision in abundance estimates; poor past fishery performance, potential increased effort size due to St. Matthew fishery closure
2000	Closed	Stock below threshold in state harvest strategy
2001	Closed	Stock below threshold in state harvest strategy
2002	Closed	Stock below threshold in state harvest strategy

Table 2. Historic Pribilof Islands blue king crab fishery stock abundance indices and harvests, 1990–2002.

Stock Abundance Indices						Harvest				
Year	Mature Biomass[a]	Percent of MSST[b]	Legal Males[c]	Mature Males[d]	Percent of Threshold[e]	Number Crabs Harvested	Pounds Harvested	Percent of Mature Biomass[f]	Percent of Legal Males[g]	Percent of Mature Males[h]
1990	10,560,034	160%	211,000	1,114,000	145%	0	0	0%	0%	0%
1991	13,844,888	210%	789,000	1,424,000	185%	0	0	0%	0%	0%
1992	12,588,266	191%	1,014,000	1,566,000	203%	0	0	0%	0%	0%
1993	12,742,588	193%	1,115,000	1,688,000	219%	0	0	0%	0%	0%
1994	14,903,096	226%	1,173,000	1,583,000	206%	0	0	0%	0%	0%
1995	24,934,026	378%	1,124,000	1,535,000	199%	172,987	1,267,454	5%	15%	11%
1996	18,957,355	287%	937,000	1,379,000	179%	127,676	937,032	5%	14%	9%
1997	11,552,104	175%	834,000	1,154,000	150%	68,603	512,374	4%	8%	6%
1998	10,670,264	162%	721,000	882,000	115%	68,513	516,996	5%	10%	8%
1999	9,193,182	139%	561,000	678,000	88%	0	0	0%	0%	0%
2000	7,407,456	112%	469,000	542,000	70%	0	0	0%	0%	0%
2001	7,032,674	107%	381,000	427,000	55%	0	0	0%	0%	0%
2002	4,534,862	69%	311,000	388,000	50%	0	0	0%	0%	0%

[a] Total mature male and female biomass, estimated by NMFS from annual eastern Bering Sea trawl survey data using area-swept method.
[b] Estimated total mature male and female biomass as percent of stock MSST specified in FMP, 6.6-million pounds.
[c] Abundance (number) of legal males estimated by ADF&G from annual eastern Bering Sea trawl survey data using CSA model (Vining and Zheng 2003).
[d] Abundance (number) of males ≥120-mm CL estimated by ADF&G from annual eastern Bering Sea trawl survey data using CSA model (Vining and Zheng 2003).
[e] Estimated number of males ≥120-mm CL as percent of stock threshold for fishery opening in state harvest strategy, 0.77-million males ≥120-mm CL.
[f] Pounds harvested during fishery as percent of estimated total mature male and female biomass.
[g] Number of males harvested during commercial fishery as percent of estimated abundance (number) of legal males.
[h] Number of males harvested during commercial fishery as percent of estimated abundance (number) of males ≥120-mm CL.

Table 3. Parameters for a four-stage model used to estimate rebuilding time periods and probabilities through computer simulations for Pribilof Islands blue king crabs. All parameters are estimated from the assessment models and observer data.

Parameter	**Males**	**Females**
Natural Mortality (*M*)	0.28	0.30
Trawl Catchability: Pre-recruit 2 / group 1	0.76	0.89
Trawl Catchability: Pre-recruit 1 / group 2	0.83	1.00
Trawl Catchability: Legals / groups 3 and 4	1.00	1.00
Pot Selectivity: Pre-recruit 2 / group 1	0.47	0.53
Pot Selectivity: Pre-recruit 1 / group 2	0.66	0.53
Pot Selectivity: Legals / groups 3 and 4	1.00	0.53
Molting Probability: Pre-recruit 2 / group 1	0.91	0.95
Molting Probability: Pre-recruit 1 /group 2	0.73	0.73
Molting Probability: Group 3	NA	0.46
Low Recruitment Cycle Length (yr)	4-9	4-9
High Recruitment Cycle Length (yr)	4-9	4-9
St. Dev. For Cyclic Recruitment	0.51	0.51
Abundance in 2002 (millions of crabs)		
Pre-recruit 2 / group 1	0.005	0.189
Pre-recruit 1 / group 2	0.031	0.320
Recruits / group 3	0.024	0.350
Post-recruits / group 4	0.277	0.287

		Male Growth Matrix: from	
	Mean Wt. (lbs)	**Pre-recruit 2**	**Pre-recruit 1**
Pre-recruit 2	2.44	0.11	0.00
Pre-recruit 1	3.59	0.83	0.11
Recruits	5.01	0.06	0.83
Post-recruits	6.89	0.00	0.06

			Female Growth Matrix: from	
	Mean Wt. (lbs)	**Group 1**	**Group 2**	**Group 3**
Group 1	1.91	0.36	0.00	0.00
Group 2	2.27	0.64	0.49	0.00
Group 3	2.67	0.00	0.51	0.59
Group 4	3.23	0.00	0.00	0.41

Table 4. Comparisons of years required to achieve ≥10%, 50% and 90% rebuilding probabilities (RP) and mean proportions of years with fishery closure and below MSST and mean annual yields (million pounds) within 10, 20 and 35 years for eight options for rebuilding strategies and no fishing (F=0) under two assumptions of recruitment dynamics and handling mortality rate (HM). Strong candidates for the proposed rebuilding strategy are shown in bold.

Option	HM	Years at RP ≥			Fishery Closure			Below MSST			Mean Annual Yield		
		10%	50%	90%	10yr	20yr	35yr	10yr	20yr	35yr	10yr	20yr	35yr
Cyclic Stock–recruitment Model													
F=0	0.0	7	9	11	1	1	1	0.45	0.26	0.17	0	0	0
1A	0.2	7	10	25	0.60	0.58	0.53	0.45	0.40	0.35	0.63	0.68	0.78
1B	**0.2**	**7**	**9**	**11**	**0.75**	**0.67**	**0.63**	**0.45**	**0.31**	**0.23**	**0.28**	**0.37**	**0.45**
2A	0.2	7	10	24	0.54	0.50	0.46	0.46	0.41	0.36	0.63	0.69	0.80
2B	**0.2**	**7**	**9**	**12**	**0.68**	**0.59**	**0.54**	**0.45**	**0.32**	**0.25**	**0.34**	**0.44**	**0.52**
2C	**0.2**	**7**	**9**	**12**	**0.70**	**0.63**	**0.58**	**0.45**	**0.35**	**0.28**	**0.44**	**0.53**	**0.62**
2D	**0.2**	**7**	**9**	**12**	**0.70**	**0.62**	**0.57**	**0.45**	**0.34**	**0.27**	**0.41**	**0.50**	**0.59**
3A	0.2	7	9	20	0.75	0.73	0.70	0.45	0.35	0.29	0.52	0.58	0.68
3B	0.2	7	9	11	0.83	0.76	0.73	0.45	0.30	0.22	0.23	0.33	0.39
1A	0.0	7	9	21	0.59	0.55	0.50	0.45	0.37	0.31	0.68	0.77	0.88
1B	**0.0**	**7**	**9**	**11**	**0.75**	**0.67**	**0.62**	**0.45**	**0.30**	**0.22**	**0.29**	**0.39**	**0.47**
2A	0.0	7	9	21	0.54	0.48	0.42	0.46	0.38	0.32	0.68	0.78	0.90
2B	**0.0**	**7**	**9**	**12**	**0.67**	**0.58**	**0.52**	**0.45**	**0.31**	**0.24**	**0.36**	**0.46**	**0.55**
2C	**0.0**	**7**	**9**	**12**	**0.70**	**0.61**	**0.56**	**0.45**	**0.33**	**0.26**	**0.46**	**0.58**	**0.68**
2D	**0.0**	**7**	**9**	**12**	**0.69**	**0.60**	**0.55**	**0.45**	**0.32**	**0.25**	**0.42**	**0.54**	**0.64**
3A	0.0	7	9	13	0.73	0.70	0.66	0.45	0.34	0.27	0.56	0.65	0.76
3B	0.0	7	9	11	0.83	0.75	0.71	0.45	0.29	0.21	0.24	0.34	0.41
1A	0.5	7	12	35	0.63	0.62	0.58	0.46	0.45	0.41	0.55	0.57	0.65
1B	**0.5**	**7**	**9**	**12**	**0.76**	**0.69**	**0.64**	**0.45**	**0.32**	**0.25**	**0.27**	**0.35**	**0.42**
2A	0.5	7	11	35	0.56	0.54	0.50	0.47	0.46	0.41	0.55	0.58	0.66
2B	**0.5**	**7**	**9**	**13**	**0.68**	**0.61**	**0.56**	**0.45**	**0.34**	**0.27**	**0.33**	**0.41**	**0.48**
2C	**0.5**	**7**	**9**	**18**	**0.71**	**0.66**	**0.62**	**0.45**	**0.37**	**0.31**	**0.41**	**0.47**	**0.55**
2D	**0.5**	**7**	**9**	**14**	**0.71**	**0.64**	**0.60**	**0.45**	**0.36**	**0.30**	**0.38**	**0.45**	**0.53**
3A	0.5	7	10	23	0.77	0.76	0.74	0.45	0.38	0.32	0.47	0.49	0.58
3B	0.5	7	9	11	0.83	0.77	0.74	0.45	0.31	0.23	0.22	0.30	0.36
Random Recruitment													
F=0	0.0	4	9	20	1	1	1	0.24	0.13	0.08	0	0	0
1A	0.2	5	17	35	0.57	0.50	0.46	0.29	0.21	0.18	0.62	0.74	0.78
1B	0.2	5	10	23	0.75	0.65	0.61	0.24	0.14	0.09	0.25	0.36	0.39
2A	0.2	5	16	35	0.47	0.39	0.35	0.29	0.21	0.18	0.62	0.75	0.79
2B	0.2	5	11	26	0.64	0.53	0.48	0.24	0.14	0.10	0.34	0.45	0.49
2C	0.2	5	11	29	0.67	0.57	0.53	0.25	0.15	0.11	0.40	0.53	0.57
2D	0.2	5	11	28	0.67	0.56	0.51	0.24	0.15	0.10	0.37	0.50	0.54
3A	0.2	5	12	31	0.76	0.71	0.69	0.25	0.16	0.12	0.45	0.58	0.62
3B	0.2	5	9	21	0.84	0.77	0.74	0.24	0.13	0.09	0.19	0.29	0.31

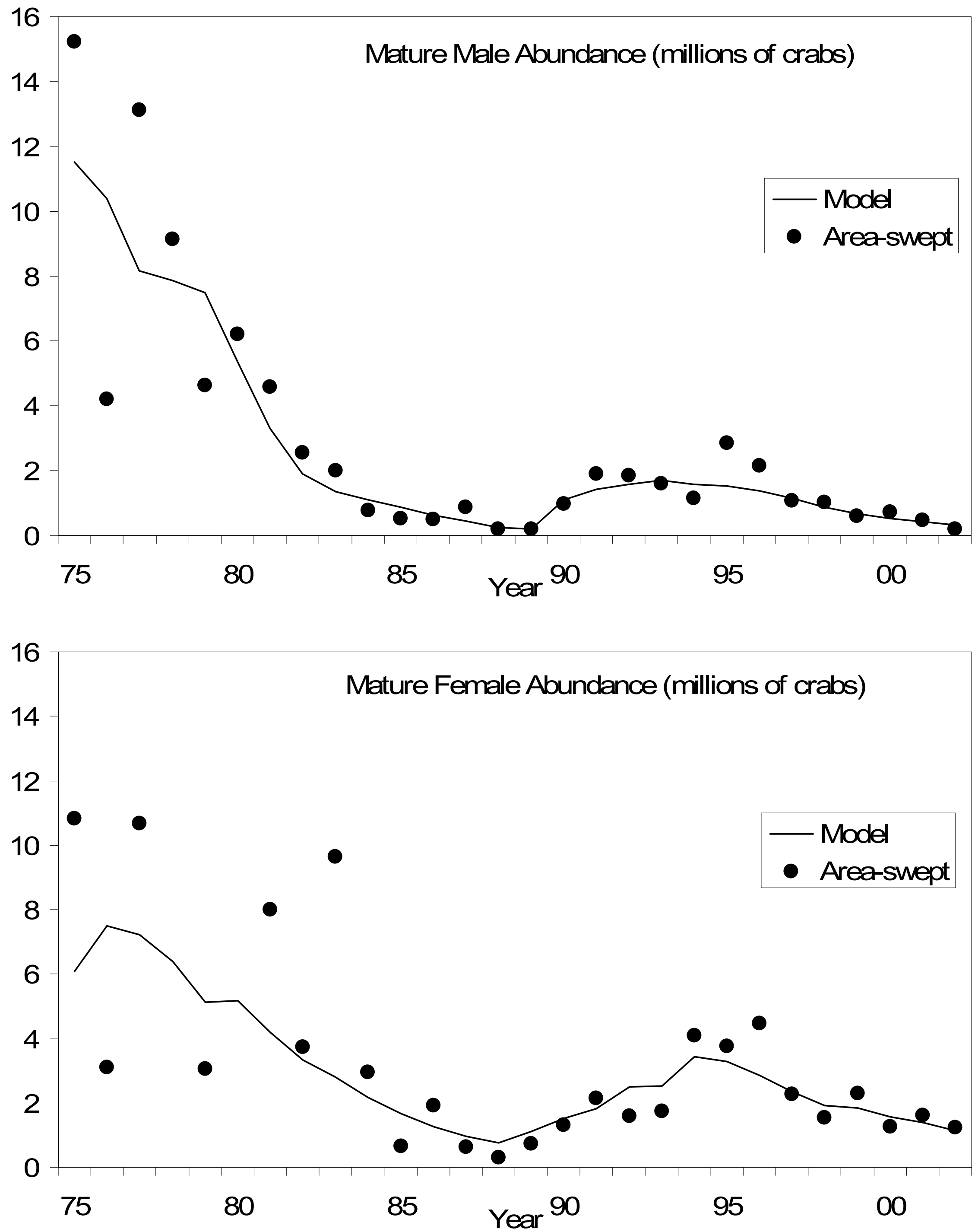

Figure 1. The four-stage model fit (lines) to area-swept estimates (dots) of mature male (>119 mm CL) and female (>99 mm CL) Pribilof Islands blue king crabs. Area-swept estimates of mature females are 57 millions in 1978 and 118 millions in 1980.

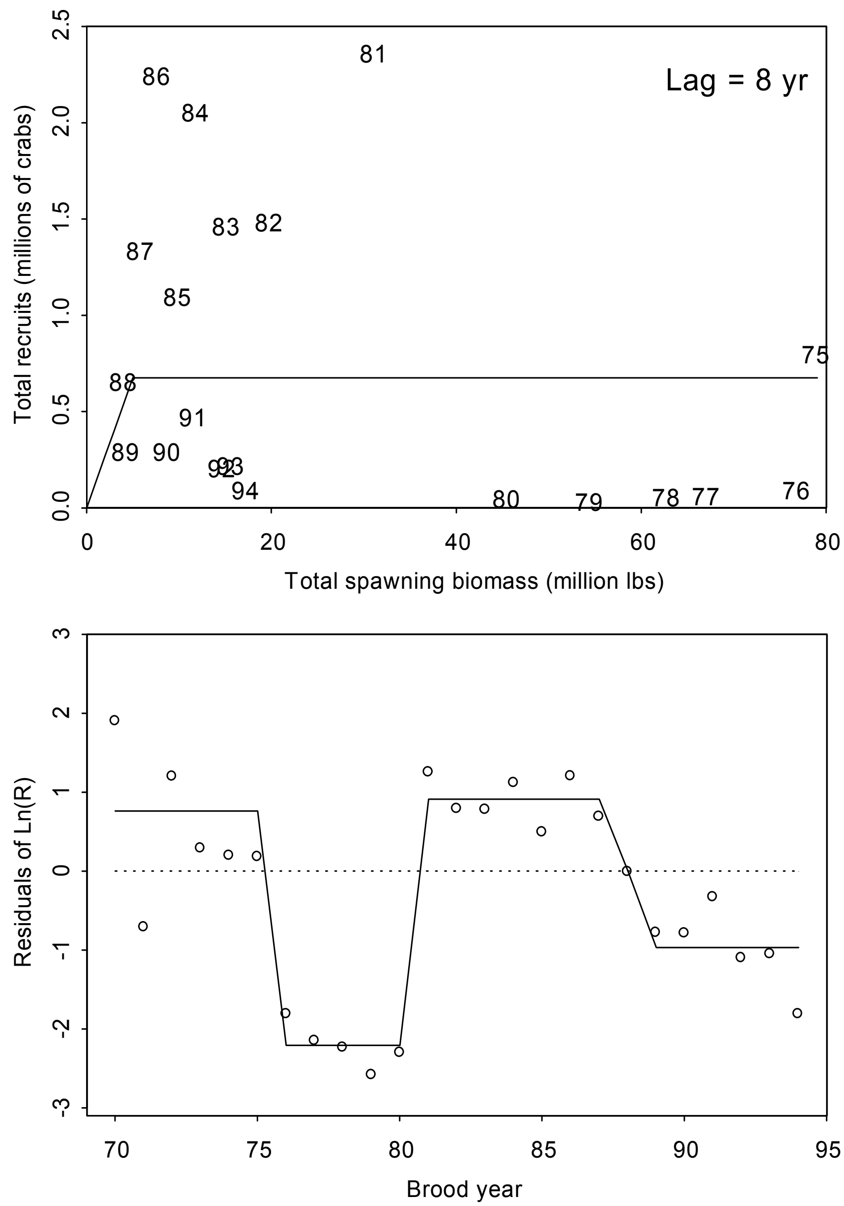

Figure 2. The relationship between total spawning biomass and total recruits at age 7 (i.e., 8-year time lag; upper plot) and residuals of logarithm of recruits from the curve (lower plot) for Pribilof Islands blue king crabs. In the upper plot, numerical labels are brood year (year of mating), and in the lower plot, the solid lines represent local means estimated from residuals.

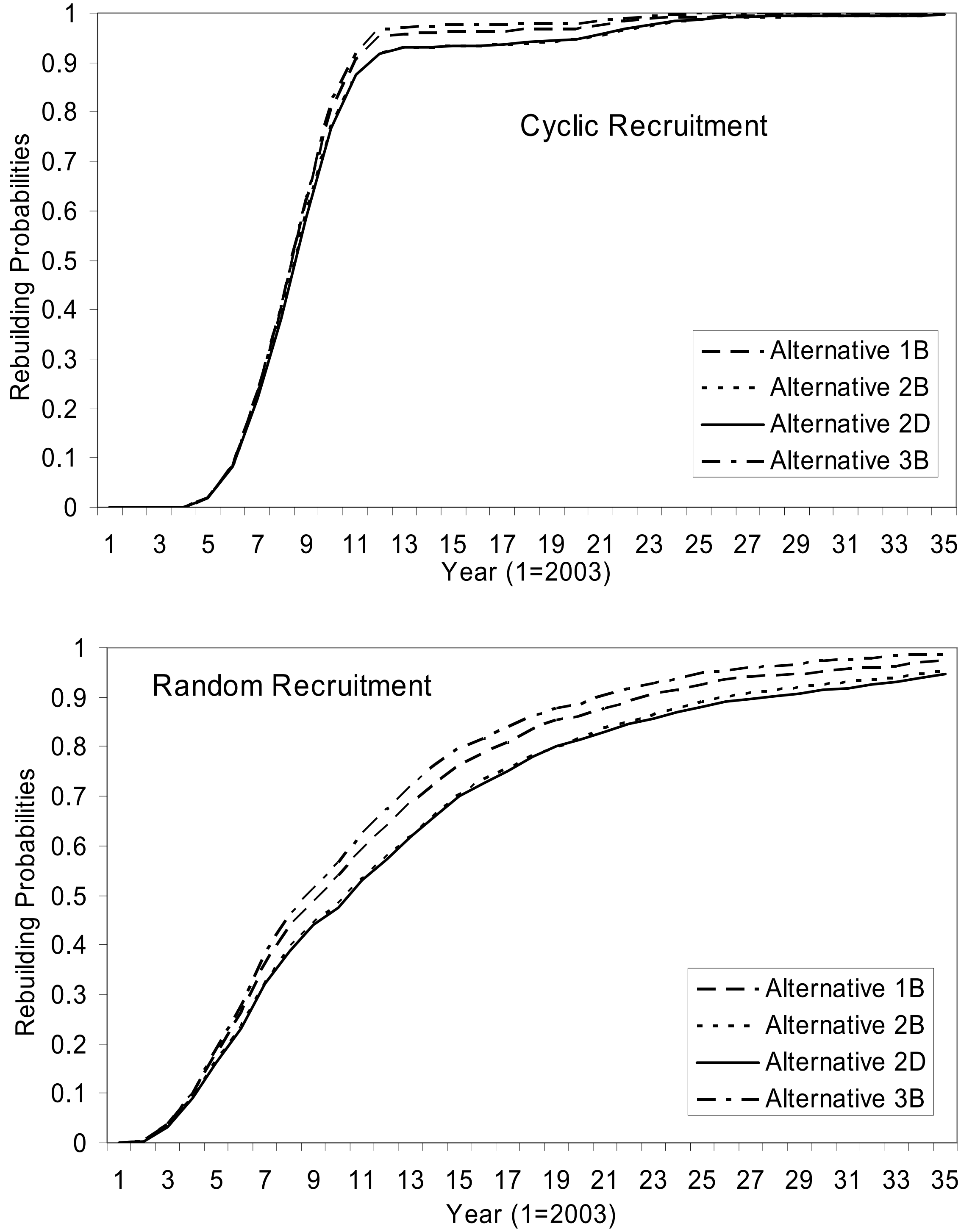

Figure 3. Estimated rebuilding probabilities under two recruitment assumptions for four options for Pribilof Islands blue king crab rebuilding harvest strategies.